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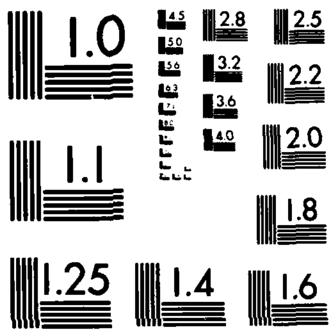
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NAVAL POSTGRADUATE SCHOOL

Monterey, California

A NOVEL OSCILLATING PLANE JET -
ITS EFFECT ON EJECTOR THRUST AUGMENTATION

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MAY 1985

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A plane subsonic turbulent jet was excited by a special oscillating nozzle. Its overall performance compares favorably with that of the vane excited jet investigated earlier. The nozzle when installed in an ejector system yielded a thrust augmentation ratio of 1.6 at an excitation frequency of 20 Hz. The dynamics of the oscillating flow was examined in the light of the Korst theory.

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TABLE OF SYMBOLS AND ABBREVIATIONS

x - longitudinal distance from the nozzle exit

y - coordinate perpendicular to x axis

H - height of the nozzle

b - width of the jet corresponding to $\frac{U_m}{2}$

R_e - Reynolds number $= \frac{HU_e}{\nu}$

U - mean velocity

U_m - maximum velocity at any station x

U_e - exit velocity

Q - volume rate of flow at any station x

Q_e - Q at $x = 0$

f_e - frequency of applied oscillation

f_x - frequency from auto-correlation

P_o - pressure in the plenum chamber

ε - entrainment ratio $= \frac{Q-Q_e}{Q_e}$

T_o - thrust of the jet

T_e - thrust of the ejector

ψ - thrust augmentation ratio $= \frac{T_o + T_e}{T_o}$

k_1 & k_2 - defined in table 1

ABSTRACT

A plane subsonic turbulent jet was excited by a special oscillating nozzle. Its overall performance compares favorably with that of the vane excited jet investigated earlier. The nozzle when installed in an ejector system yielded a thrust augmentation ration of 1.6 at an excitation frequency of 20HZ. The dynamics of the oscillating flow was examined in the light of the Korst theory.

I. INTRODUCTION

It is well known that a turbulent jet can be stimulated to entrain more fluid by subjecting it to excitation [1-9]. This property of the jet has innumerable practical applications, many of them yet to be exploited. For example, in aeronautical engineering it could be utilized to enhance the thrust of an ejector installed in a V/STOL aircraft.

It is observed that, while an axi-symmetric jet can easily be excited by the application of axial or transverse disturbances or even acoustically, a plane jet is found to respond only to an anti-symmetric perturbation [15]. Recent experiments carried out to excite a plane jet, by an oscillating thin airfoil or vane located in the potential core region, were quite successful [4,5], and high rate of mixing, coupled with larger entrainment, were achieved by this technique. When installed in an ejector, the thrust was more than that produced by a steady jet [10].

Though the utility of the vane excitation method has been demonstrated on a laboratory scale, its suitability for practical application to an aircraft system is yet to be established. The drag of the airfoil or vane in its oscillating mode and the structural instability of this thin vibrating member in a hostile environment can pose severe operational problems.

To alleviate the above constraints, a novel oscillating mechanism with a high efficiency nozzle was designed. The flow characteristics of this jet and its performance in an ejector system form the main theme of this report.

II. EXPERIMENTAL SET-UP

The novel feature of the jet used in this investigation is the method of excitation. A converging nozzle was employed with its upper and lower surfaces in the exit region segmented for reciprocating action to impart oscillations to the flow. The frequency of reciprocation could be varied from 0 to 35 HZ by controlling the speed of the motor which was connected to the segments through a cam-gear mechanism (Fig. 1). The maximum throw of the tip was 1.0 cm. When the nozzle was in the symmetric position with each lip extended halfway, the width of the nozzle was 0.5 cm. at the exit independent of the location of the lips. The length of the nozzle was 3.8 cm. A set of honeycombs and fine mesh screens were installed in the plenum chamber of the jet to damp out disturbances from upstream. Dry air was supplied to the plenum chamber by a large rotary compressor through a dump tank and a pressure regulating valve. The jet assembly, along with the oscillating mechanism was mounted on special low friction bearings constraining the movement of the whole unit to the axial direction. Strain gauge mounted force sensing devices were attached to the system for measuring the thrust of the jet.

The ejector was fabricated from sheet metal in the form of a rectangular duct 9.5 cm. long and 4.0 cm. wide whose height could be varied from 7-47 cm. in steps of 5 cm. (Fig. 2). Static pressure holes were provided at suitable intervals on the bottom wall of the duct. A short 5.2° (half angle) diffuser was attached to the duct in one of the experiments. Thrust generated by the ejector was measured independently by a strain gauge force recording device, to an accuracy of $\mp$ 2 %.

Mean velocity profiles were measured across the width of the jet at its midspan with a fine 2mm diameter pitot-static tube coupled to a differential

pressure transducer. A small 1.0 cm diameter disc-type static pressure probe incorporating a Kulite pressure transducer was fabricated for measuring mean static pressure as well as part of the fluctuating component (Fig .3). The turbulence signals from this probe were processed by a Seicor-SA1-42 real time correlator.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

All the experiments were carried out with a plenum chamber pressure of 1.137 atmospheres and the exit velocity (U_e) was 160 meters/sec. An oscillating frequency (f_e) of 20 HZ was used throughout the investigation except in one case. The Reynolds number $R_e = \frac{U_e H}{\nu}$ was 4.8×10^4 for the steady jet.

The mean velocity profiles were measured at 9, 18, 27, 36 and 45 nozzle widths downstream of the exit for the steady as well as for the excited jet (Figs. 4-8). In both cases the width (b) of the jet (b) increased linearly with x (Fig. 9) following the relations

$b/H = 0.22\ (x/H + 0.9)$ - steady jet ---------------------------------(1)

and

$b/H = 0.54\ (x/H - 9.26)$ - oscillating jet ---------------------------(2)

The mean velocity along the center line (U_m) decayed faster for the excited jet (Fig.10). The decay rate was found to be

$(U_m/U_e)^{-2} = 0.10\ (x/H + 1.5)$ - steady jet ---------------------------(3)

an

$(U_m/U_e)^{-2} = 0.213\ (x/H - 0.706)$ - oscillating jet -------------------(4)

The flow entrained by the jet was estimated by integrating the mean velocity profiles. For the steady case the entrainment ratio (ε) increased linearly with x beyond x/H = 20 (Fig. 11); the variation is given by

$\varepsilon = 0.8 + 0.73\ (x/H)$ --(5)

similarly for the oscillating jet is (Fig. 10)

$\varepsilon = 1.15 + 0.92\ (x/H)$ for x/H 20 ---------------------------------(6)

The thrust of the jet and the ejector were measured independently. For a plenum pressure of 1.137 atomsphere the jet alone produced an axial force of

29.2 Newtons both for the steady and the excited states. Ejector thrust was frequency dependent up to f_e = 14 HZ beyond which its value was essentially constant (Fig. 12). Based on this observation, the remaining investigations were carried out at 20 HZ to eliminate frequency dependence in some of the results.

The influence of the ejector height was examined by varying S/H from 14 to 88. Thrust increased initially up to S/H of 40 for the steady jet followed by decrease in φ (Fig. 13). A somewhat similar trend was observed with the oscillating jet with the maximum at S/H = 45. The upper values of φ for the steady and oscillating cases were 1.5 and 1.6, respectively. With the diffuser attached to the duct (S/H = 48), the thrust of the ejector increased by nearly six percent for both steady and oscillating conditions.

The mean velocity profiles at x = 46 cm were surveyed in the parallel duct with x/H of 44, without the diffuser (Fig. 14). Excitation did increase mixing but it was only partial, as could be observed from the gradients in the velocity profiles. The entrainment ratio (ε) for the case of the steady jet as estimated from the above velocity distribution was 4.6. With the excited jet ε was 6.35.

IV. DISCUSSIONS

The decay of mean velocity along x is less for this jet in the steady state when compared with others (Table 1) and the value of k_1 is closer to the case with very thin laminar boundary layers at the nozzle exit[16]. A similar situation could be anticipated in the present experiment as the flow in the converging nozzle is subjected to severe acceleration. The growth of the jet is the same as for the others. It is interesting to observe that in general the angle of spread of a plane turbulent jet (k_2) is not highly influenced by the initial conditions except by a shift in the origin. The average value of k_2 is $0.22 \mp .02$.

The overall performance of the reciprocating nozzle is comparable with that of the oscillating vane system. There is fair agreement in the growth of the jet as well as in the entrainment (Figs. 9 & 11) when the comparison is made with the results of Platzer et al[8] for the same Reynolds number and oscillating frequency (f_e) with the vane at its highest pitching mode. The data from other experiments could not be made use of since the test conditions were different.

The fluid dynamics of a steady plane turbulent jet is yet to be fully understood. Excitation adds further complexity to the problem. It has been hypothesized that even a steady jet experiences an inherent flapping motion, a behavior inferred from space-time as well as from autocorrelation of fluctuating velocity components. The period of correlation (t) is found to increase with x. Cervantes and Goldschmidt[12] observed that there exists a Strouhal number $\frac{f_x b}{u_m}$, where $f_x = 1/t$, the value of which is a constant equal to 0.11 and independent of x. Similar results were obtained in the present

investigation (Fig. 15), using the auto correlation measurements made with the disc pressure probe. The period corresponding to the second zero in the auto-correlation (Fig. 15) was considered for evaluating f_x. $\frac{fxb}{U_m}$ was found to be constant equal to $0.10 \mp .02$ in the region $x/H = 6$ to 60. This value was independent of Reynolds number in the range of 25000 to 93000, the upper and the lower limit of the test facility (Fig. 16). Since the signals from the pressure transducer were not strong enough at large distances from the nozzle for data processing, the above measurements were restricted to $\frac{x}{h}$ of 60.

The influence of the imposed periodic oscillations on the already existing flapping motion of a steady jet is still a matter for speculation. According to Korst[14], a favorable coupling between the natural and applied oscillations is required for the amplification of the jet and this could occur at any location along the axis. Based on this concept, Korst defined a pair of Strouhal numbers ST_N for the steady jet and ST_e for the excited one, defined by

$$ST_N = f_x H/U_m \text{ and } ST_e = f_e H/U_m$$

with

$$F_x b/U_m = 0.11 \text{ and } b/H = 0.083\ (x/H + 6.62) - \text{Ref. 12}$$

$$ST_N = 1.325\ (x/H + 6.62)$$

When ST_e and ST_N are nearly equal there should be an amplification resulting in a large spread and entrainment of the jet. Since f_x is estimated from statistical considerations this phenomenon might not be spontaneous.

The above hypothesis of Korst is examined using the available experimental results on plane excited jets (Figs. 17 & 18). For the reciprocating nozzle ST_e/ST_N is less than unity by an order of magnitude. But

for the experiments of Badri Narayanan and Raghu[9] ST_e and ST_N are almost equal near the exit of the nozzle except for $f_e = 10$ HZ. Beyond x/H of 40 there is reduction in entrainment where the difference between the two Strouhal numbers is large. This trend is in agreement with Korst's hypothesis. The results of Lai and Simmons[6] indicate agreement between ST_e and ST_N only around x/H of 60, for f_e of 20 and 30 HZ.

The data of Bernal and Sarohia[15] are found to be insufficient for this analysis. However, based on an approximate evaluation of the velocity decay (Fig. 18), ST_N and ST_e were calculated. Both Strouhal numbers were nearly equal at x/H of 17 for an excitation frequency of 500 HZ, the frequency at which the amplification of the jet was spontaneous.

The above discussions lead to the speculation that there might be more than one mechanism involved in the excitation of a plane jet. Resonance amplification is noticeable when the amplitude of imposed oscillations is small. Acoustic disturbances fall under this category[13,17]. The response is somewhat localized in the region of perturbation, a trend observable in the experiments of Badri Narayanan and Raghu[9] (Fig. 17). In this process the amplitude of the input disturbance does not affect the overall results. Only the frequency is of importance.

For larger disturbances the resonance mode will be present, however its role will be secondary, when compared to the large periodic eddies generated by the imposed oscillations. These large scale motions which will be periodic in the beginning will break down into smaller ones as they are convected downstream. In this process the transport of mass and momentum will be significantly modified from that of a steady jet. It is obvious that the amplitude, as well as the frequency of the imposed disturbance, have to be considered in determining the overall flow characteristics of the jet. The

next phase of the present research activity is to investigate the fluid mechanical details of this flow with special emphasis on the structure of turbulence and its role in the mixing process.

TABLE I.

INVESTIGATOR	K_1	C_1	K_2	C_2	
1. PRESENT CASE	0.10	1.50	0.22	0.9	
2. PLATZER et all (Ref. 8)	0.325	-0.46			
3. HUSSAIN & CLARK (Ref. 16)	0.01132	-2.1	0.24	1.9	thin laminar B. L.
	0.1739	-0.63	0.23	-2.16	thin turbulent B. L.
4. BADRI NARAYANAN and RAGHU (Ref. 9)	0.485	0.412	0.212	1.89	
5. LAI and SIMMONS (Ref. 6)	0.171		0.226	0.26	
6. CHAMBERS and GOLDSCHMIDT (Ref. 13)	0.136	-13.4	0.188	-10.4	
7. BERNAL and SAROHIA (Ref. 15)	0.216	-17.56	0.179	2.49	

$$(Um/Uo)^{-2} = K_1(X/H + C_1)$$

$$b/H = K_2(X/H + C_2)$$

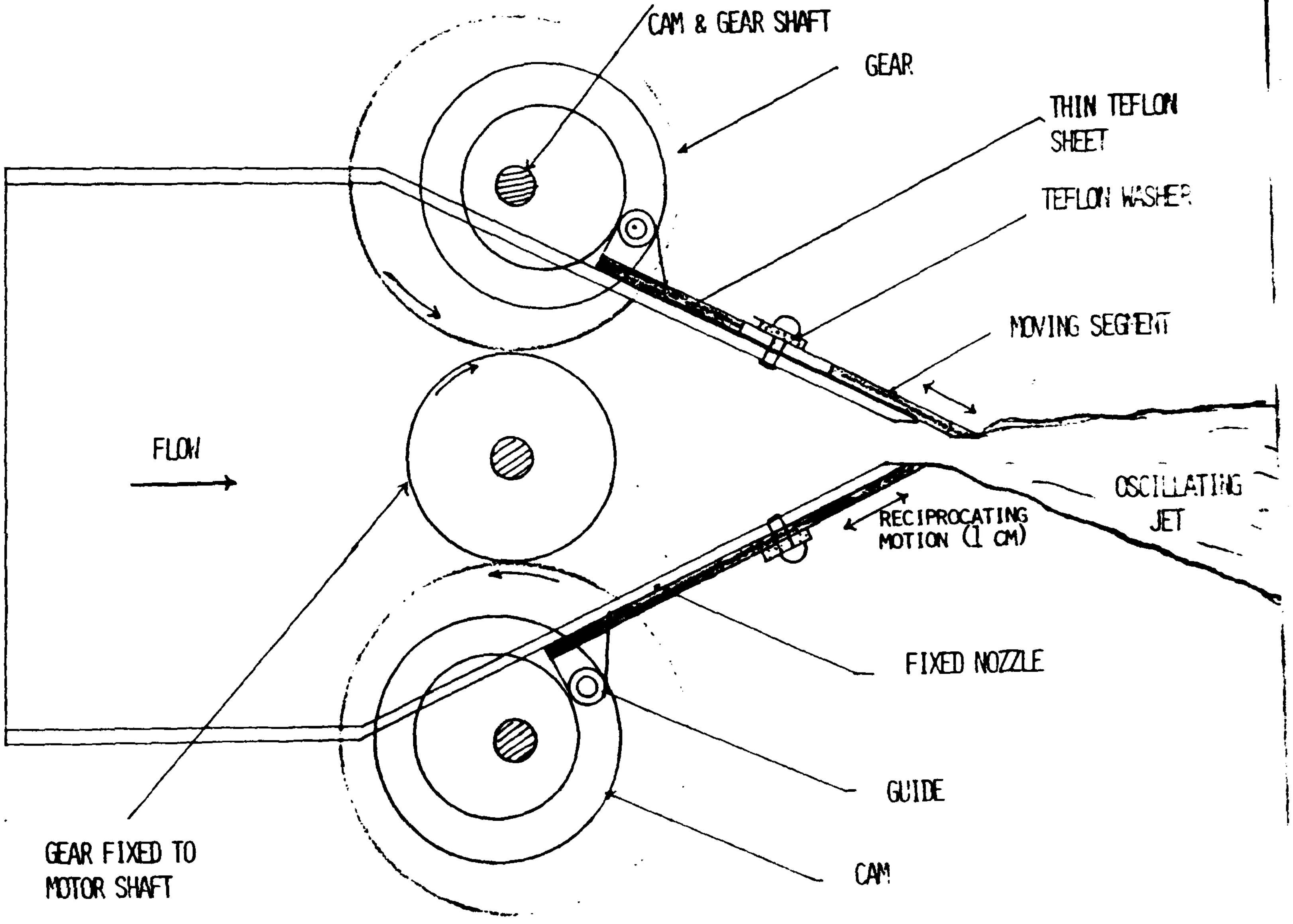

FIG.1 MECHANISM FOR OSCILLATING THE NOZZLE

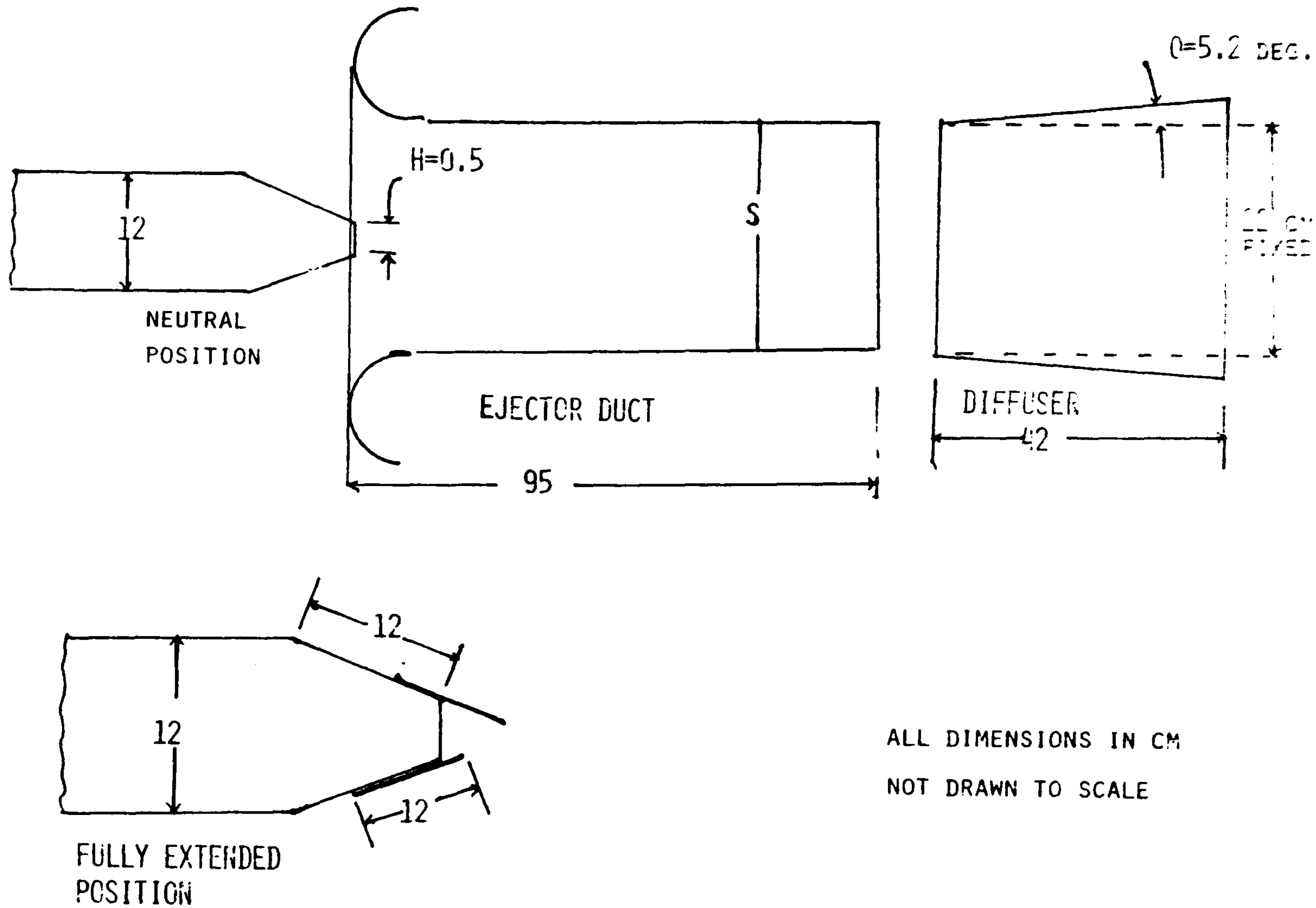

FIG. 2 – EJECTOR SYSTEM

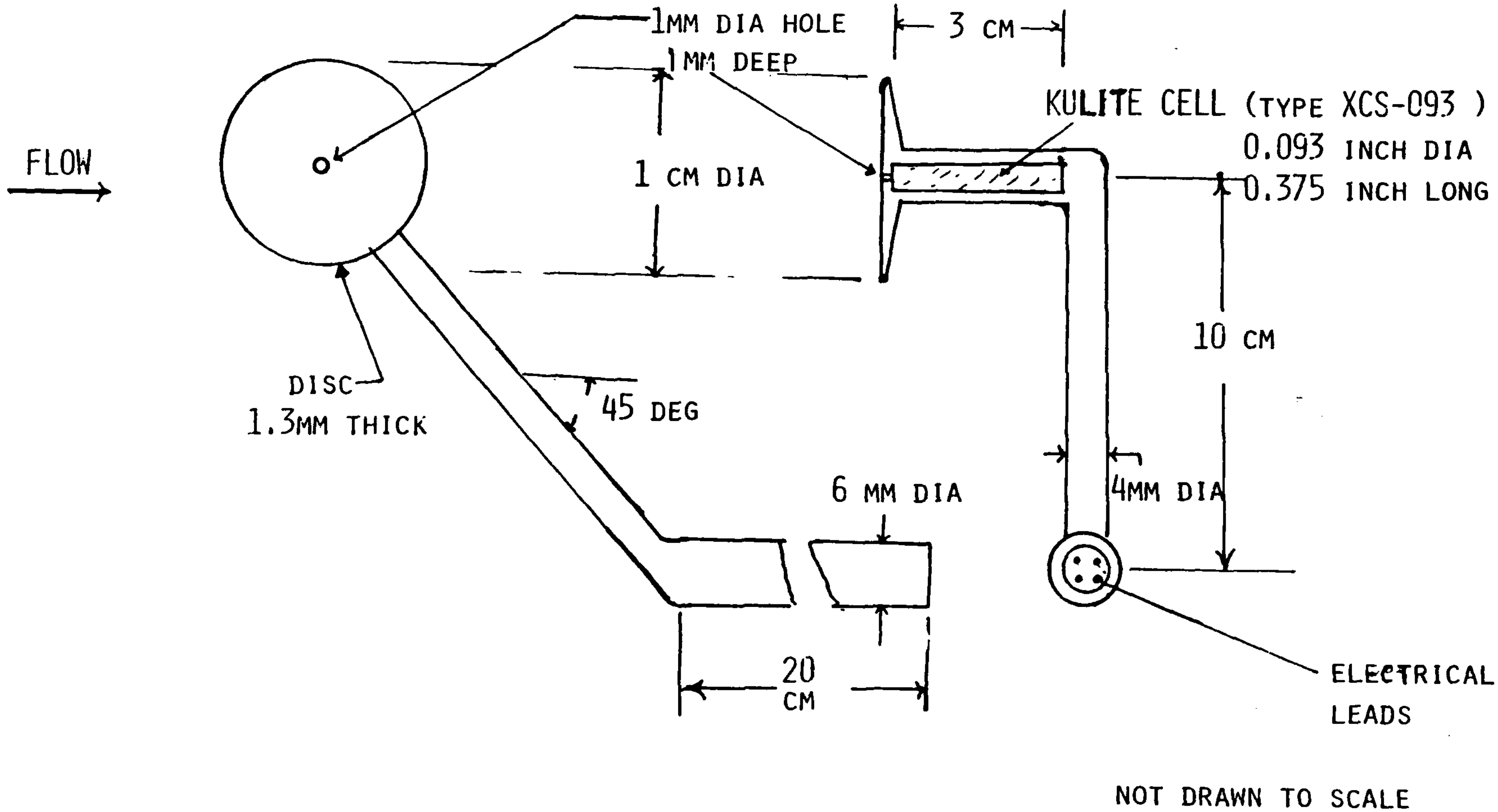

FIG. 3-DISC TYPE PRESSURE TRANSDUCER

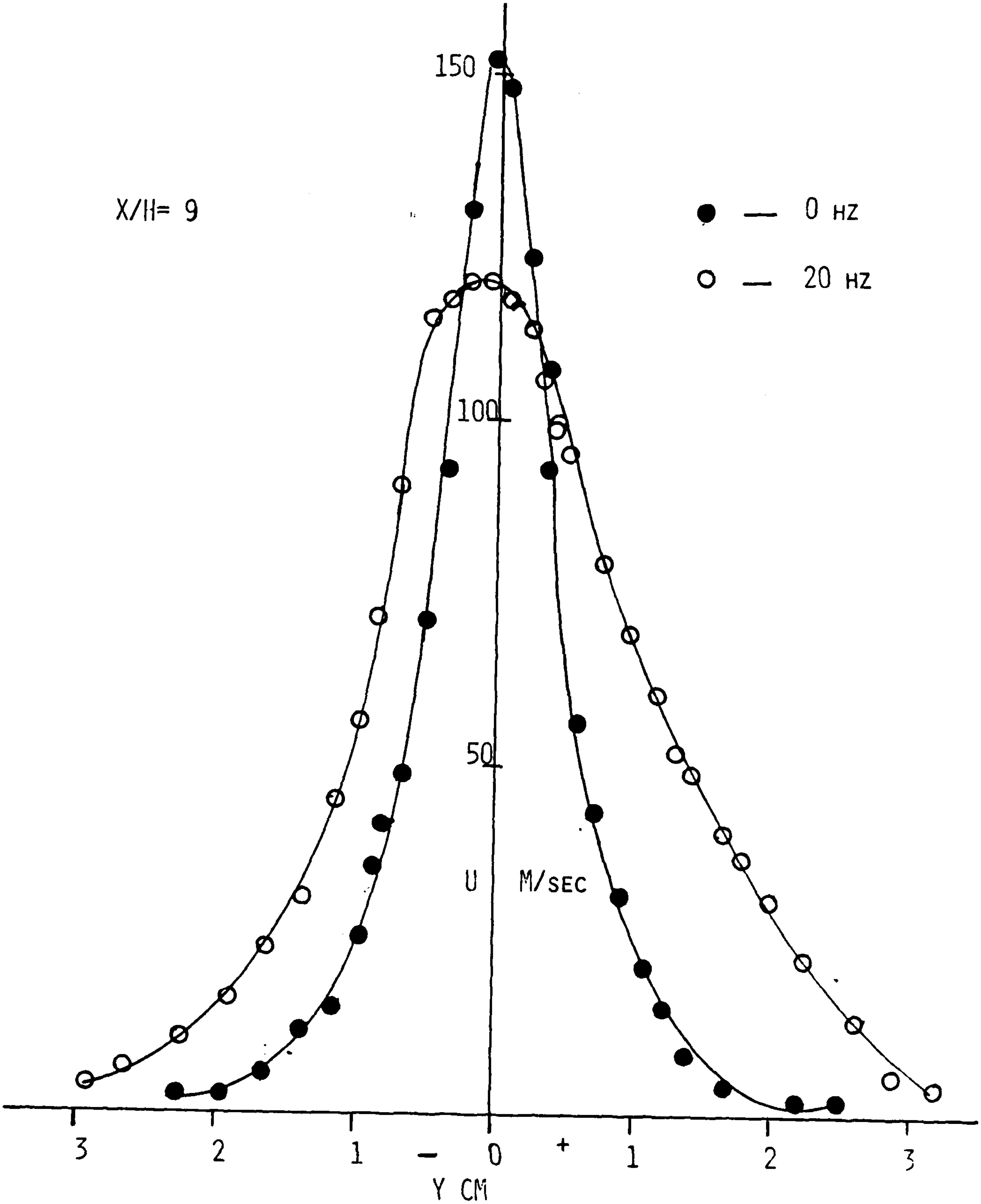

FIG. 4 - MEAN VELOCITY PROFILES

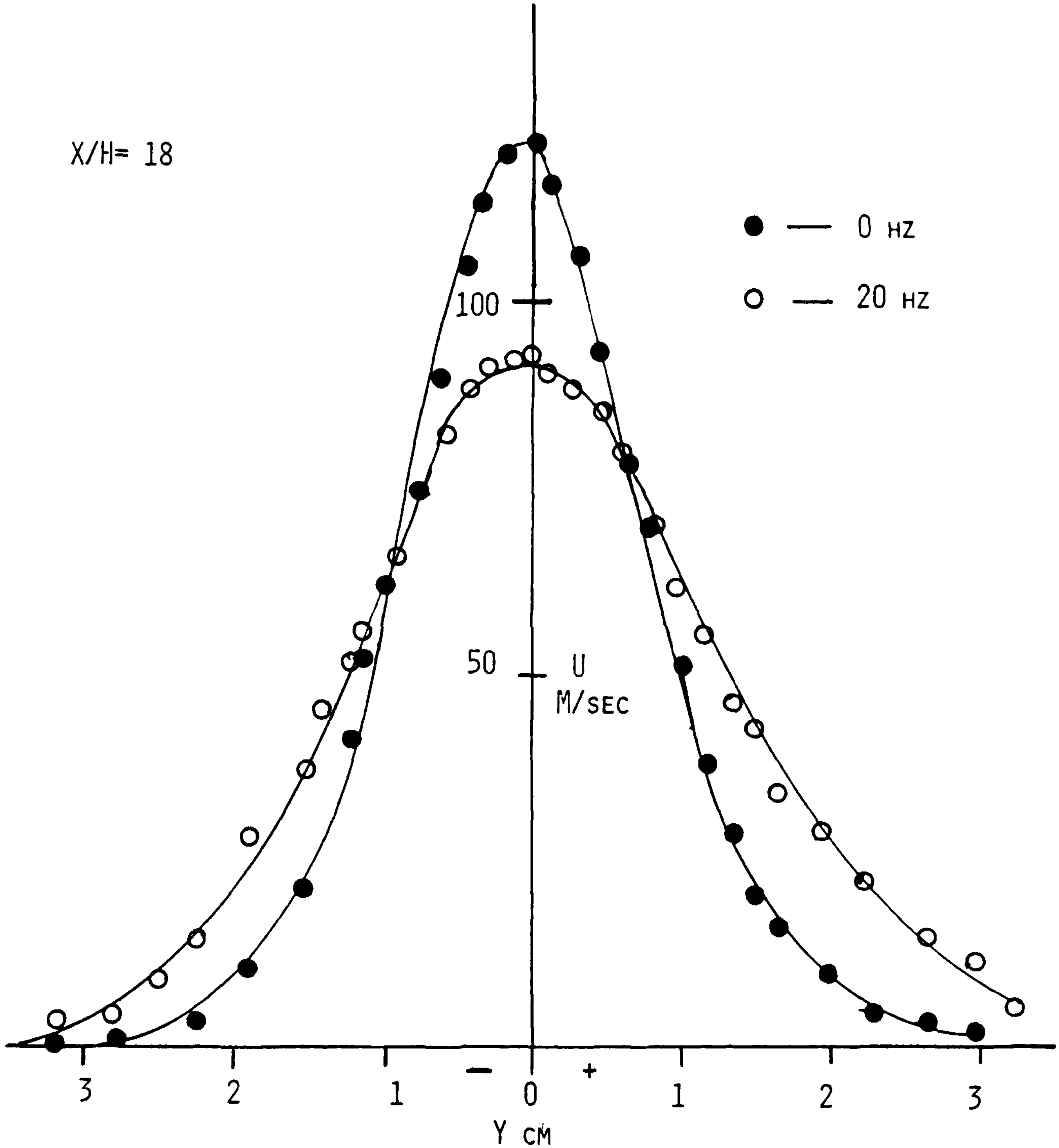

FIG. 5-MEAN VELOCITY PROFILES

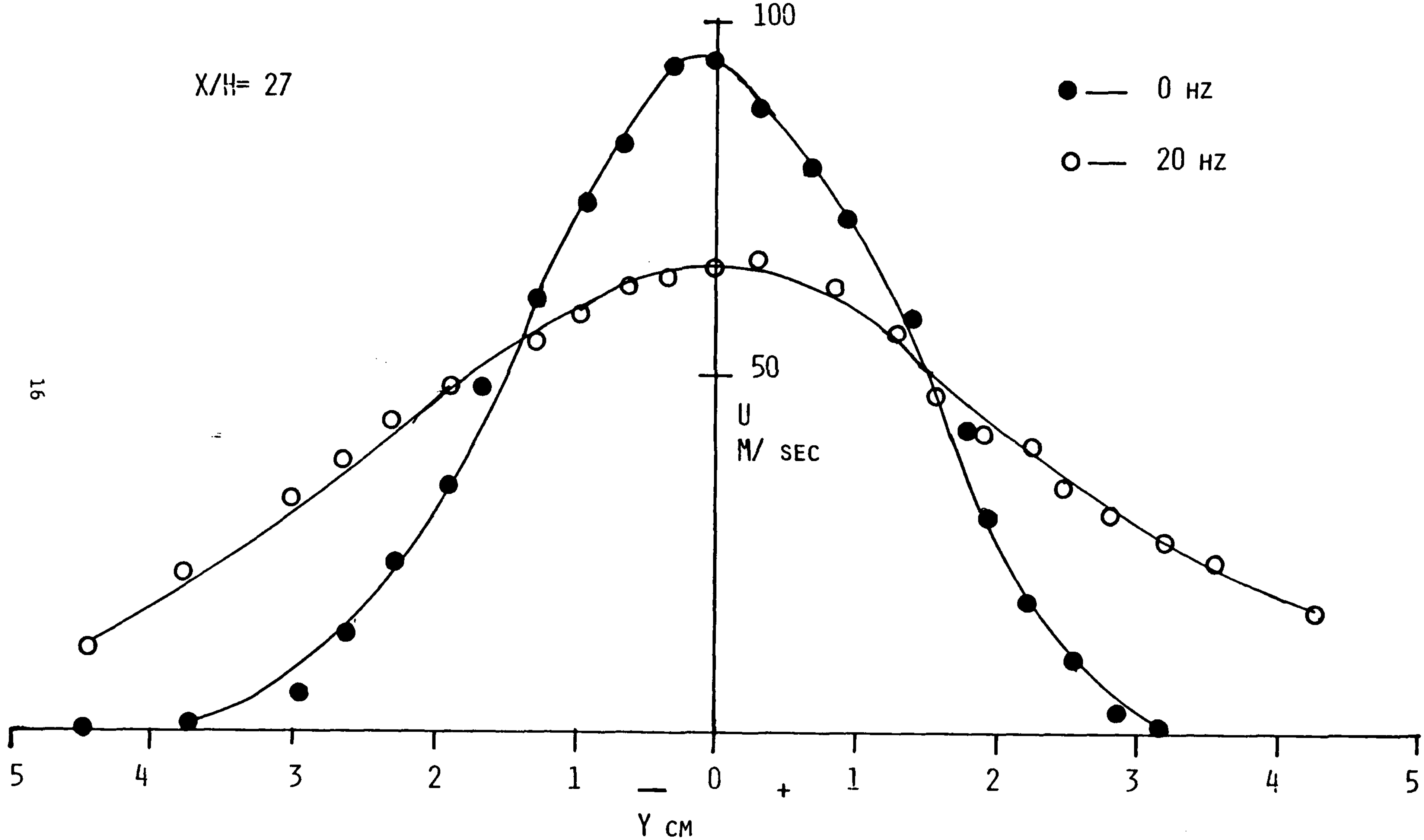

FIG.6 MEAN VELOCITY PROFILES

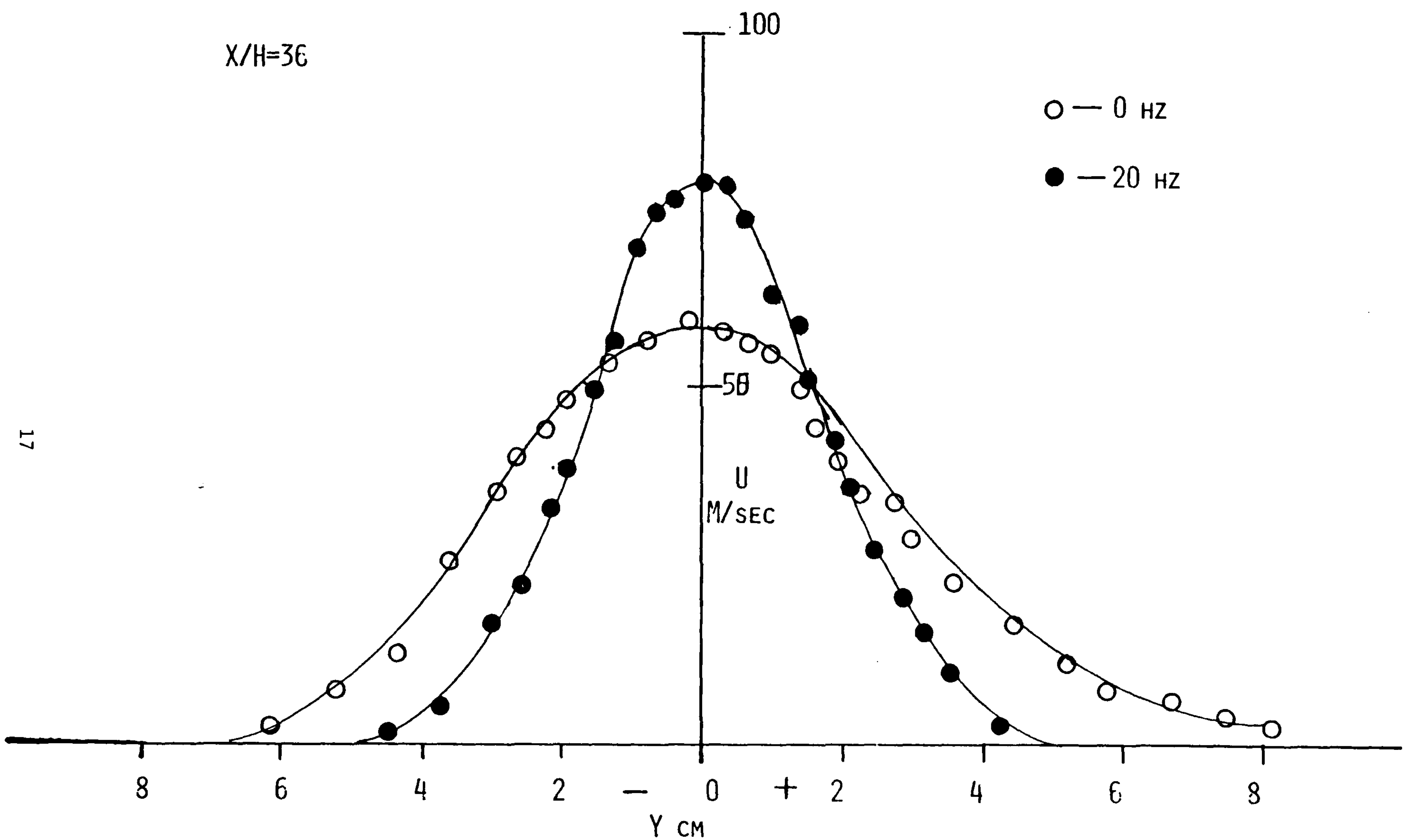

FIG. 7 MEAN VELOCITY PROFILES

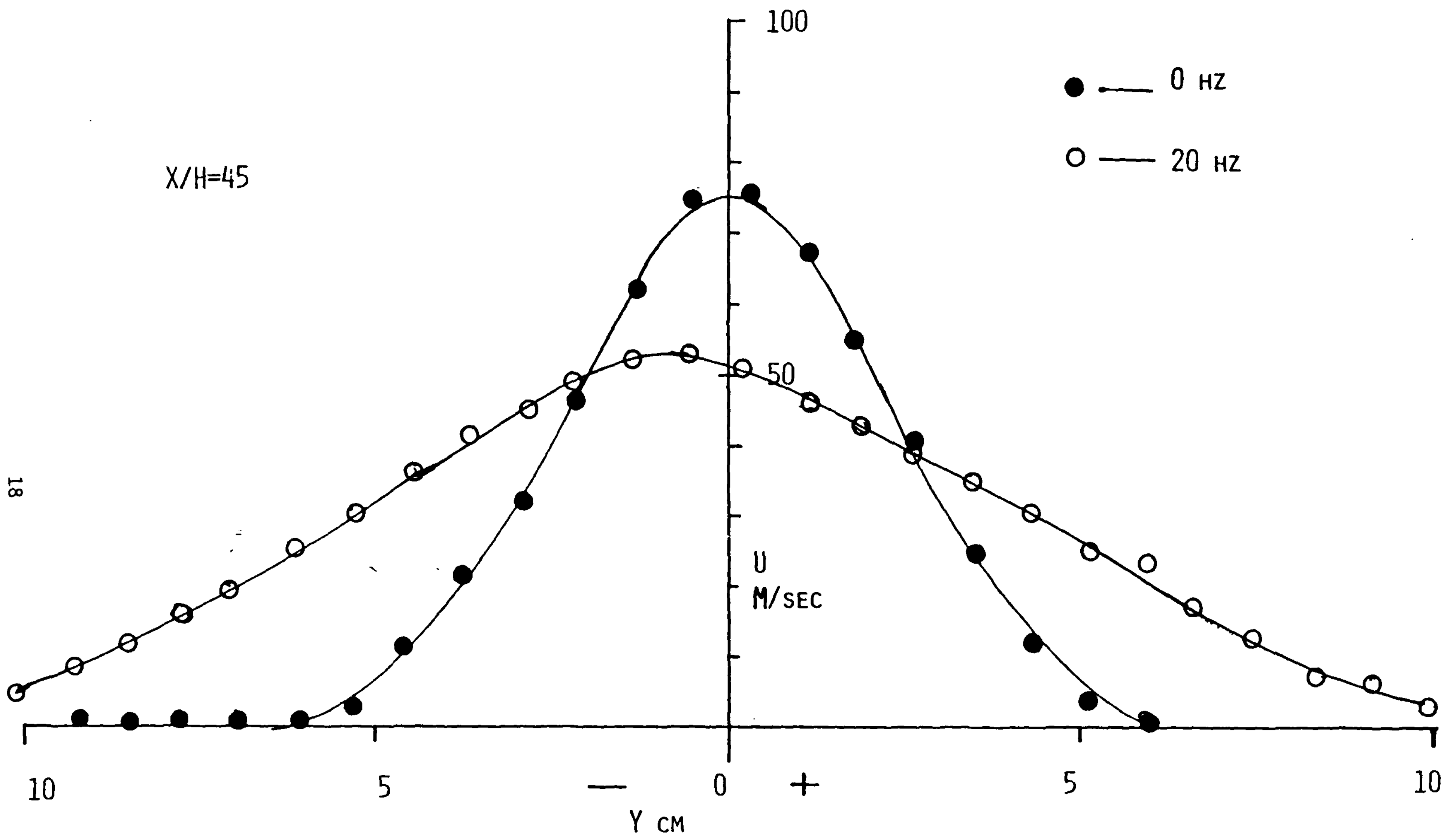

FIG.8 MEAN VELOCITY PROFILES

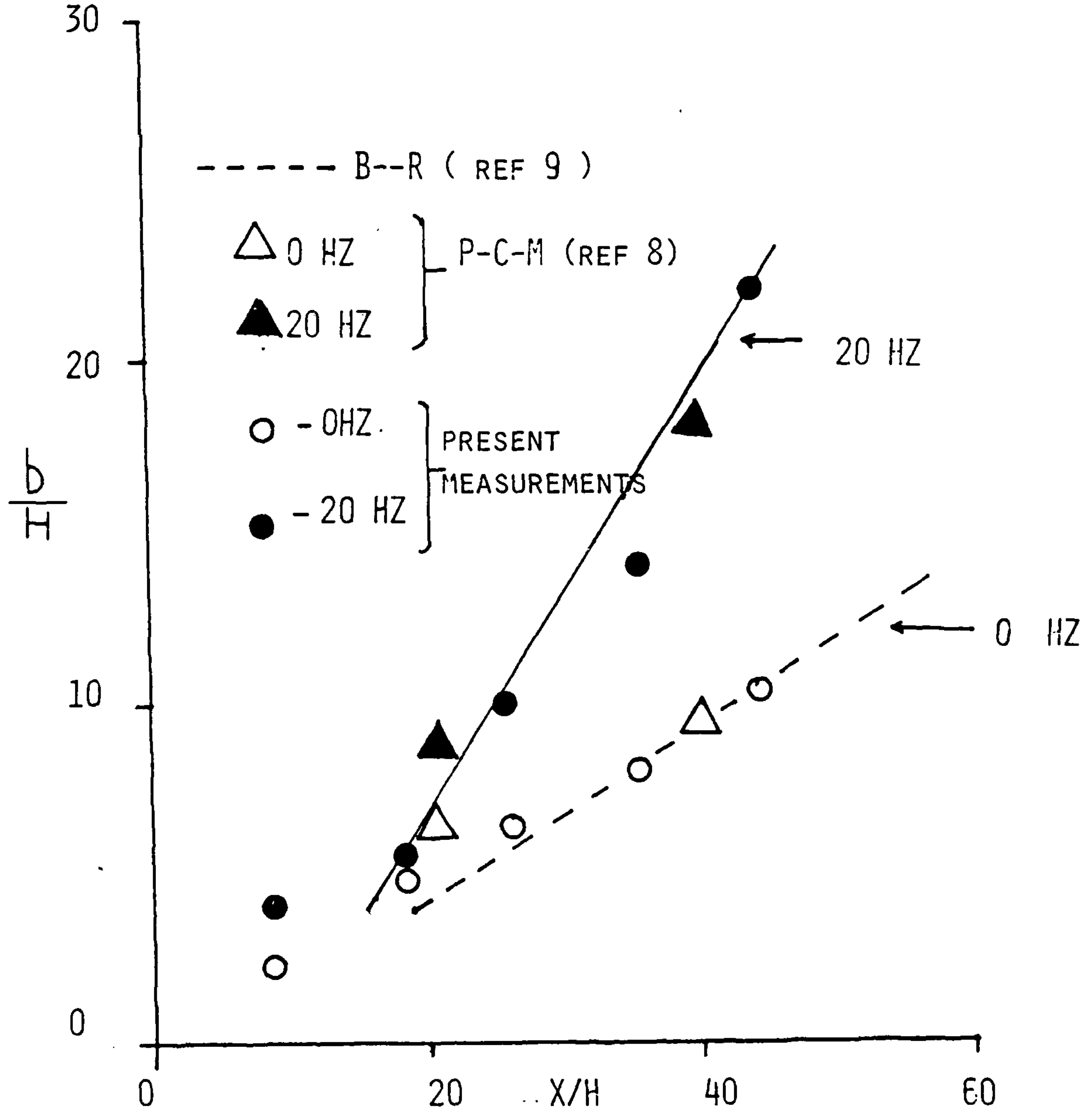

FIG.9 GROWTH OF JET WITH EXCITATION

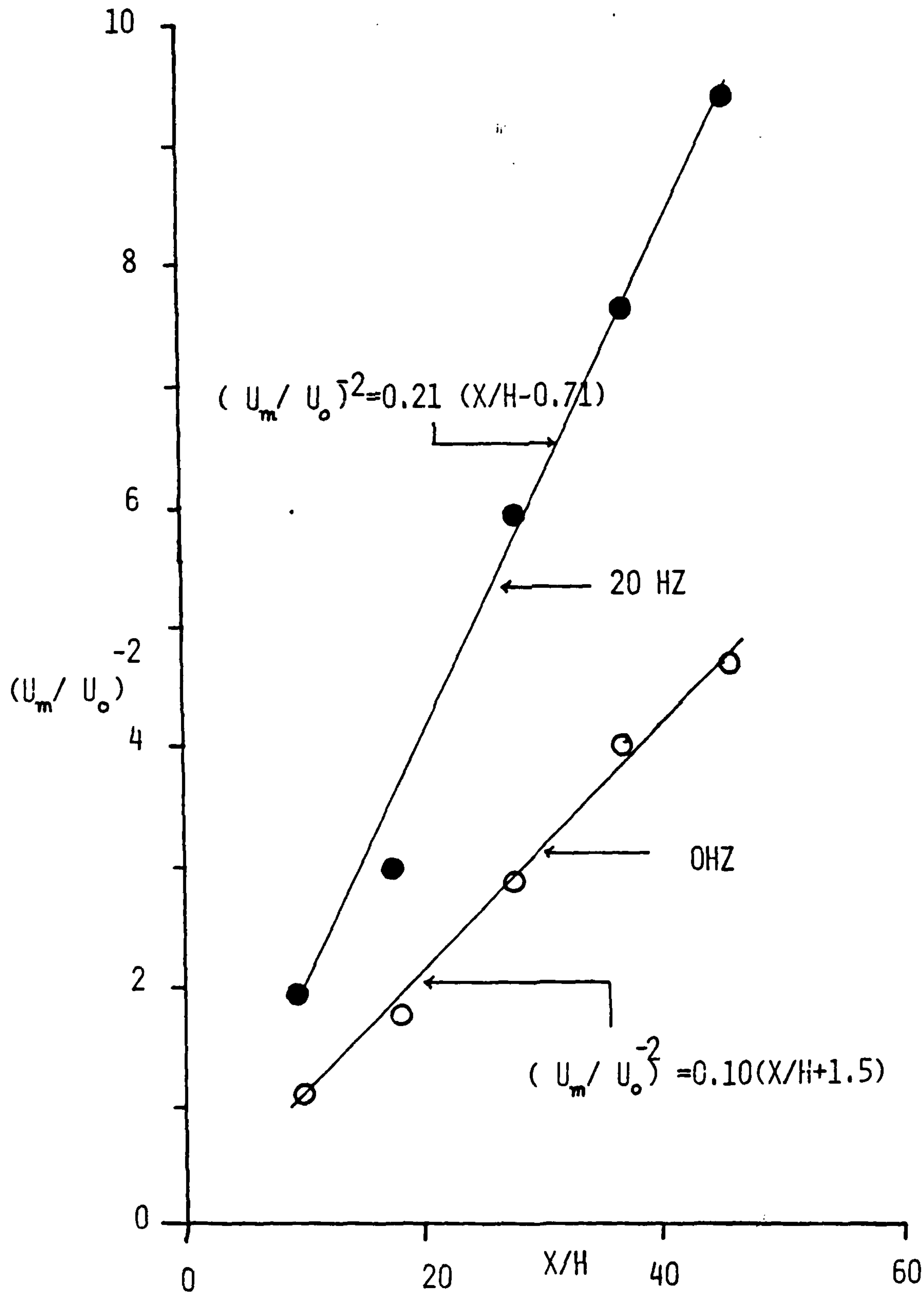

FIG.10-DECAY OF MEAN VELOCITY ALONG THE CENTER LINE

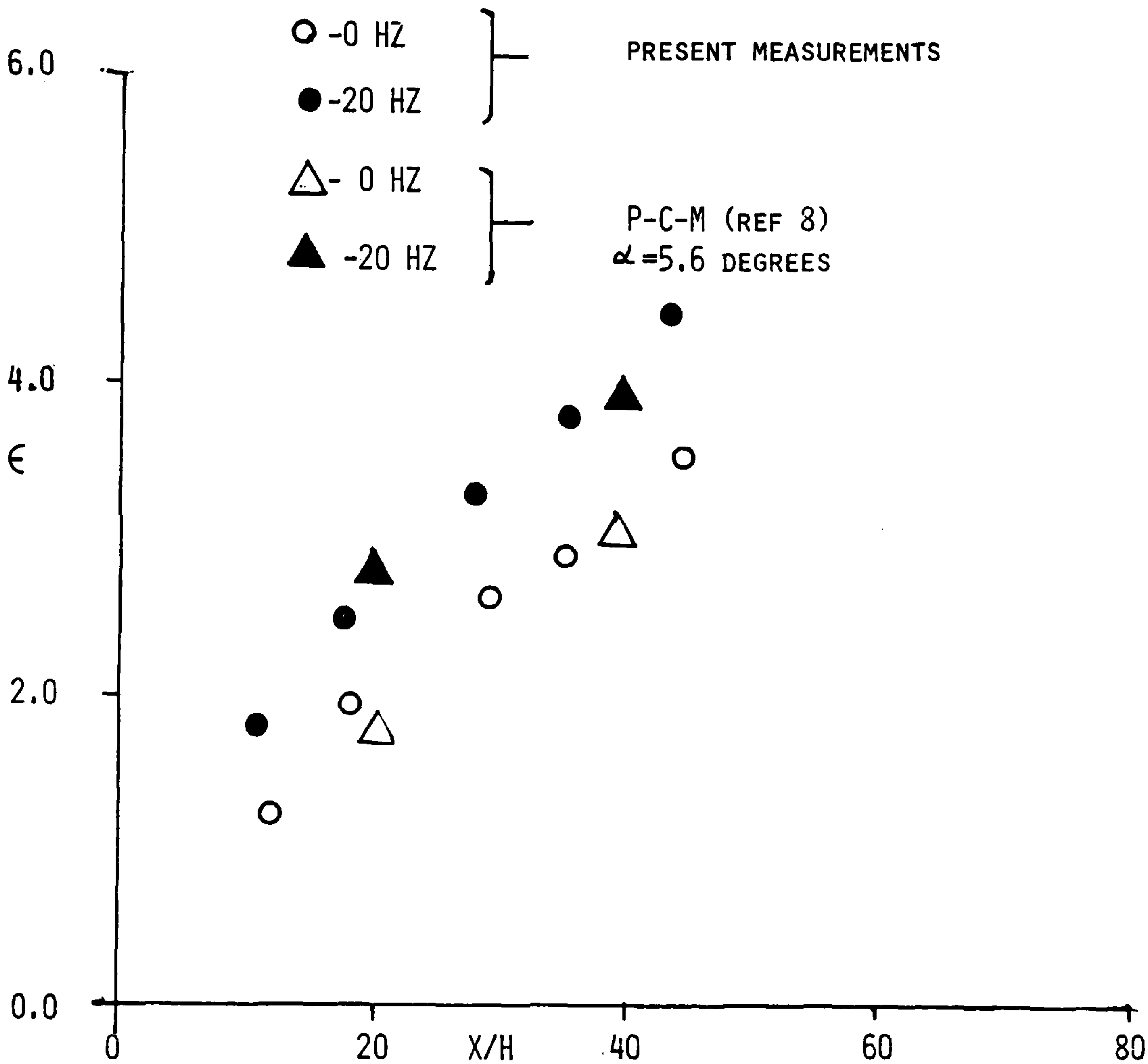

FIG. 11 - EFFECT OF EXCITATION ON ENTRAINMENT

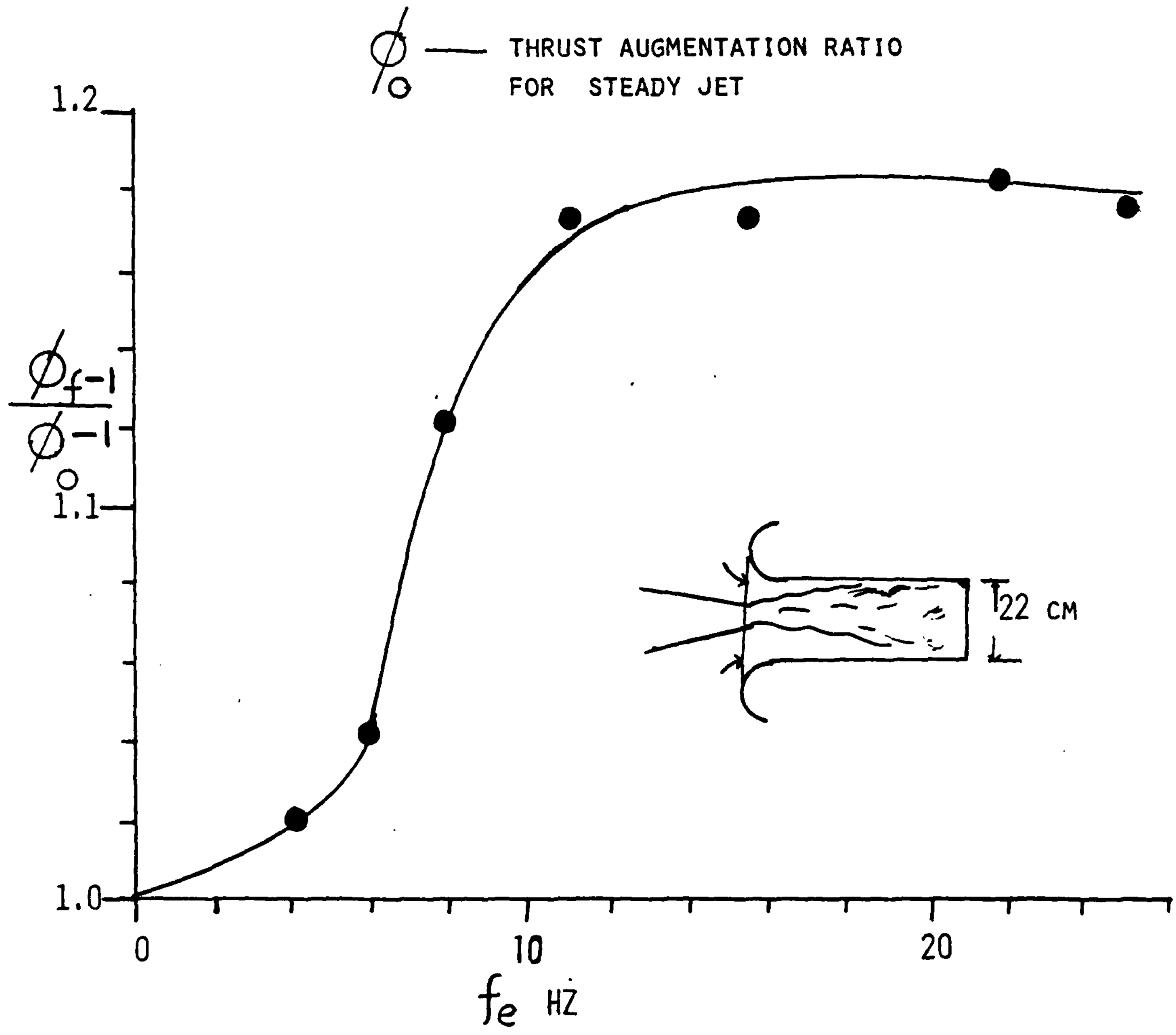

FIG. 12-EFFECT OF OSCILLATING FREQUENCY ON EJECTOR THRUST

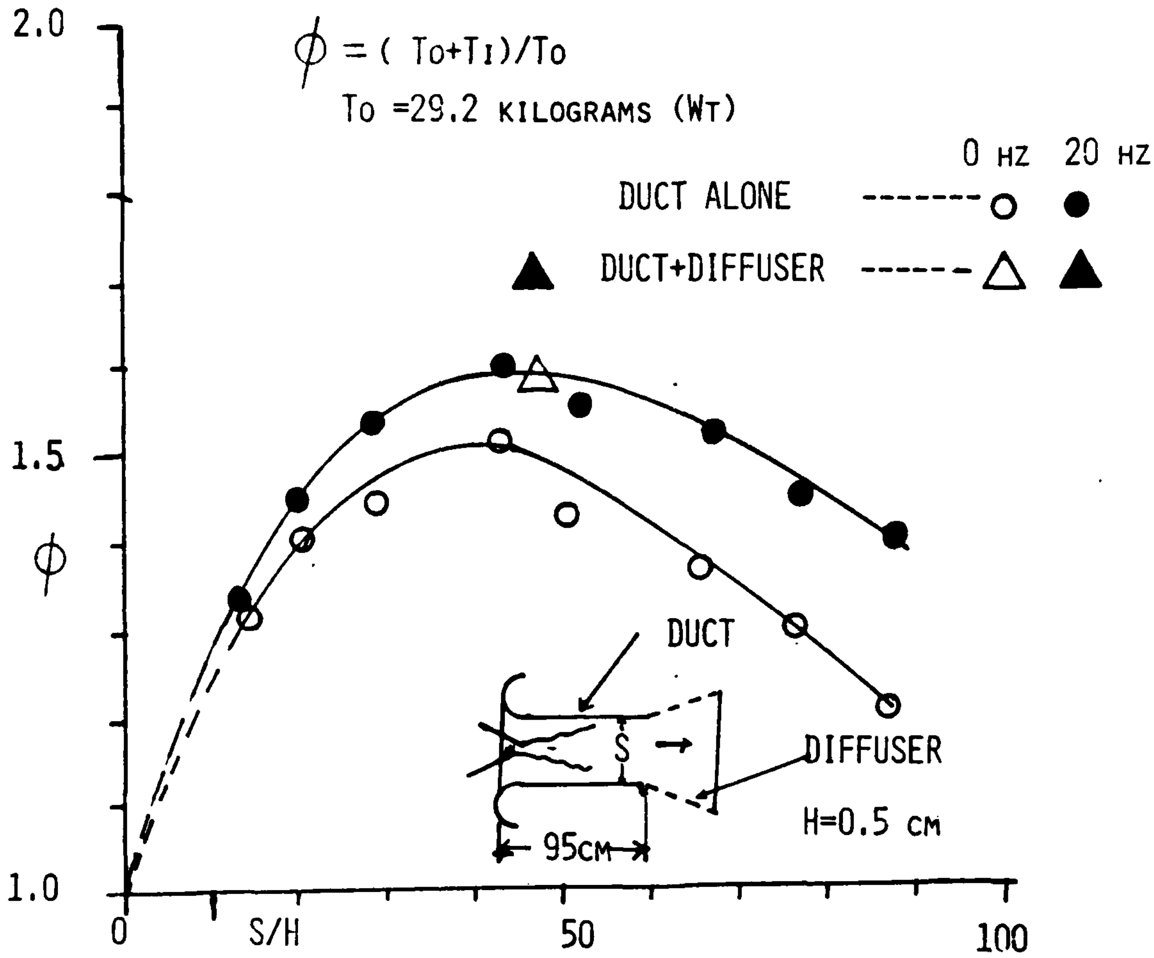

FIG.13 VARIATION OF THRUST WITH HEIGHT OF DUCT

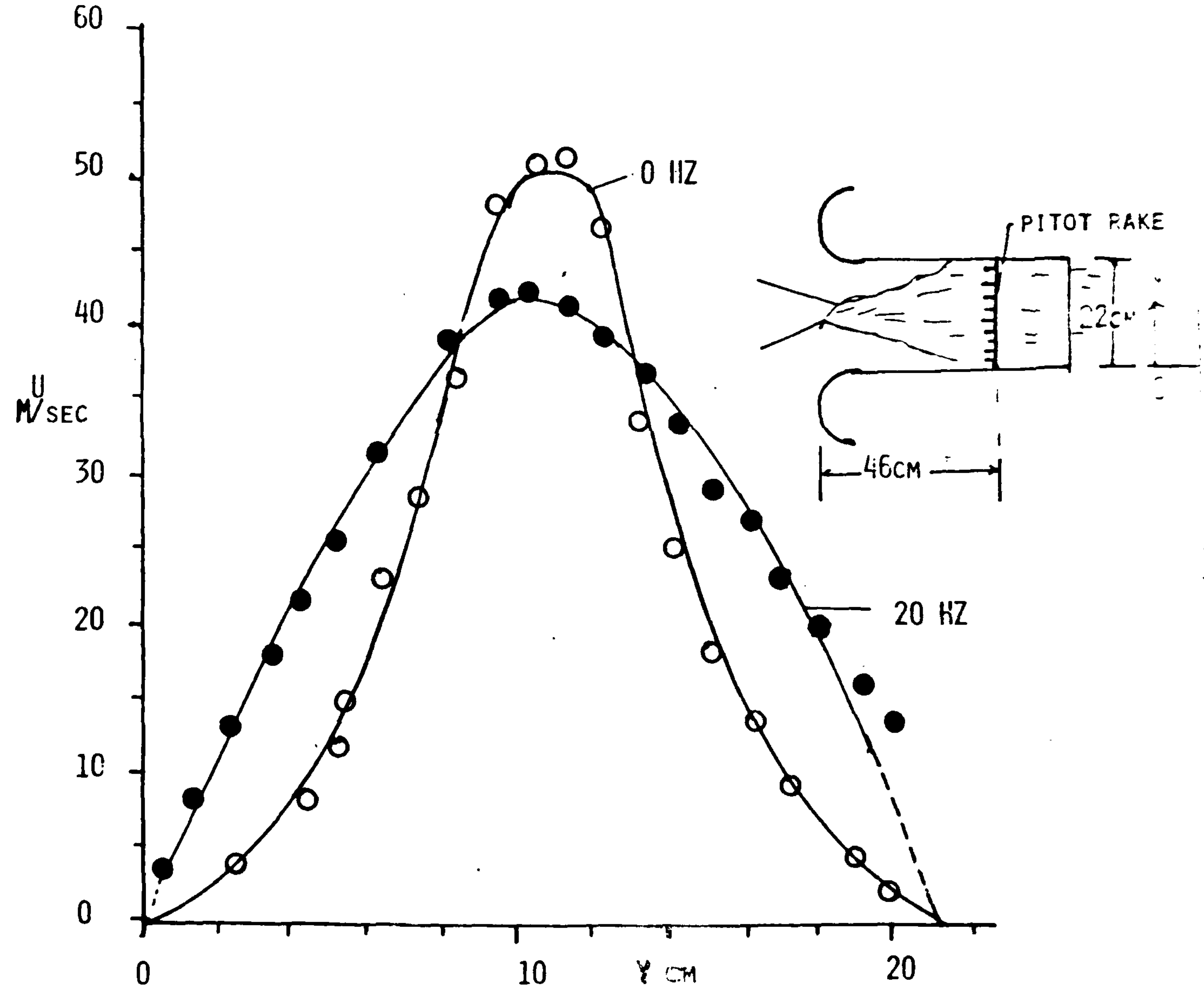

FIG.14 MEAN VELOCITY DISTRIBUTION IN THE DUCT

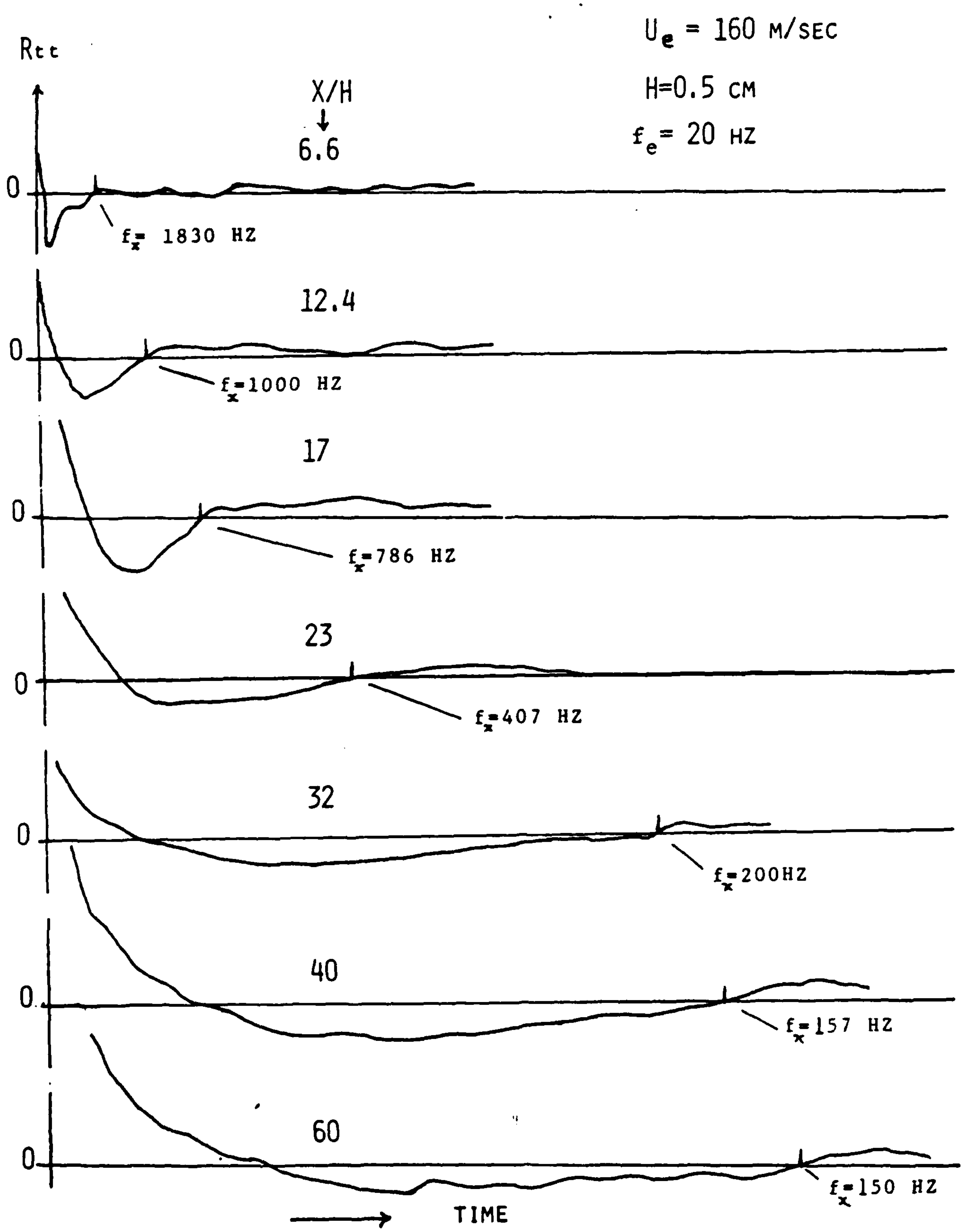

FIG. 15 AUTOCORREATION OF FLUCTUATING PRESSURE

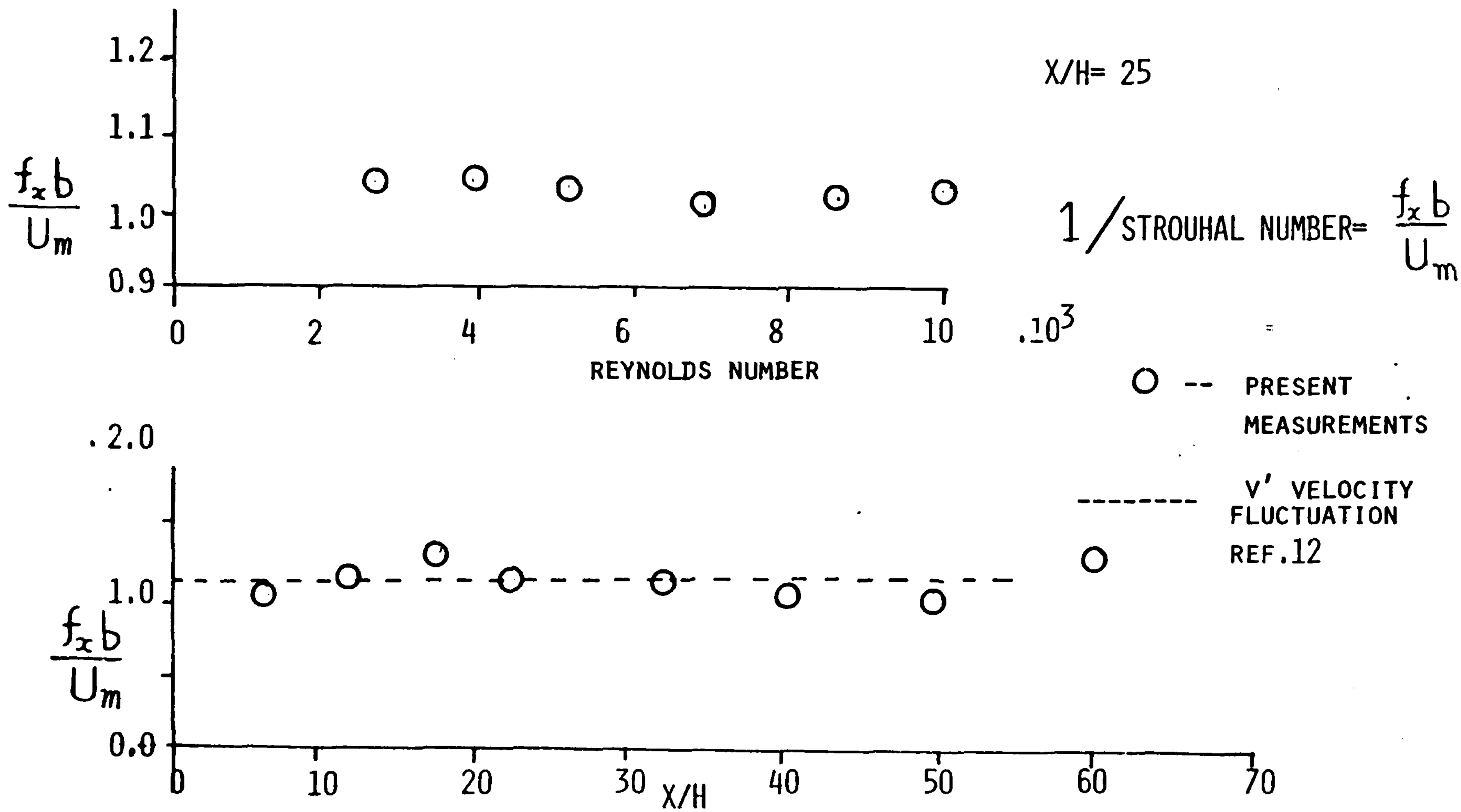

FIG.16 - STROUHAL NUMBER ESTIMATED FROM AUTOCORRELATION MEASUREMENTS

PRESENT MEASUREMENT $f_e = 20$ HZ

X/H	10	20	30	40	50	60	70	80
ST_N	.08	.050	.036	.028	.023	.020	.017	.0153
ST_E	.00066	.00093	.0011	.0013	.0014	.0015	.0016	.0018

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X/H →	10	20	30	40	50
ST_N →	.079	.050	.036	.028	.023
f_e ↓		ST_E			
10	.0084	.013	.0156	.022*	.021*
30	.026	.0398*	.048*	.066*	.066
50	.047*	.072	.078	.102	.131
70	.070*	.093	.114	.133	.162
90	.095*	.113	.147	.196	.267

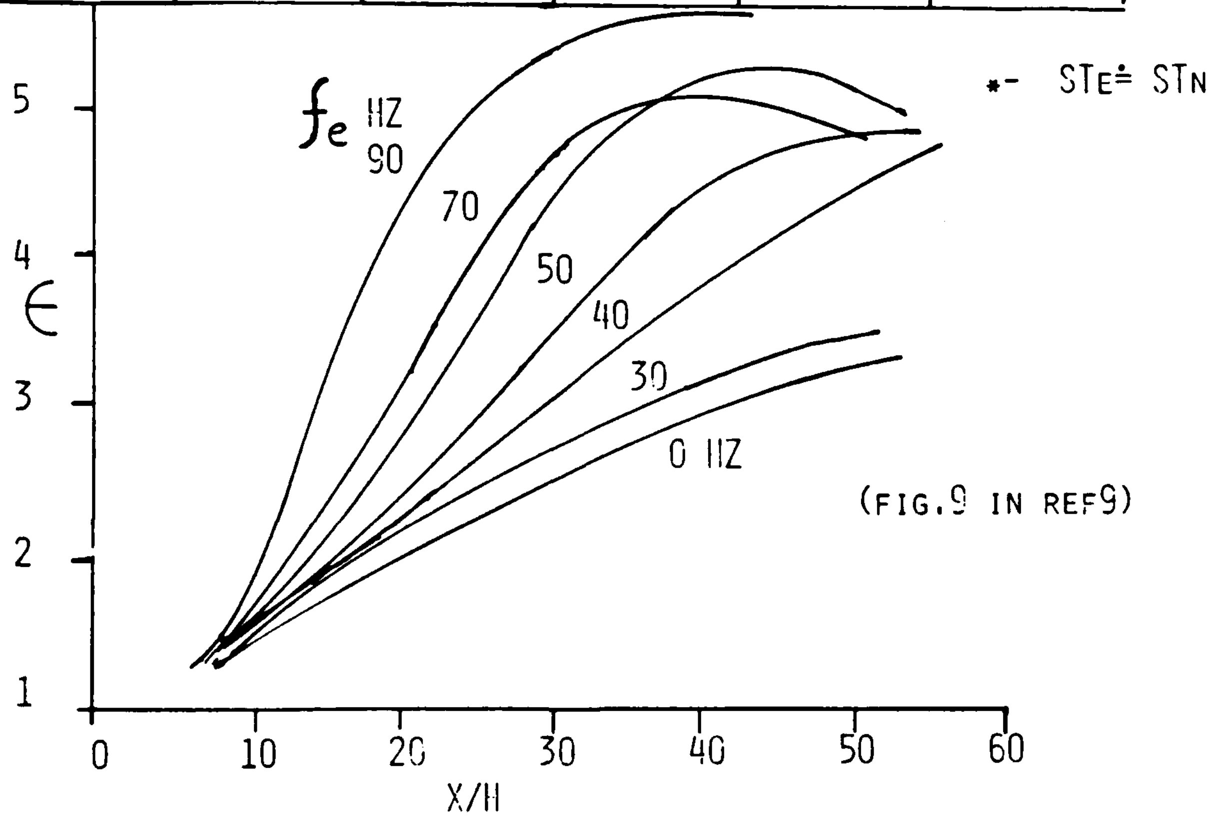
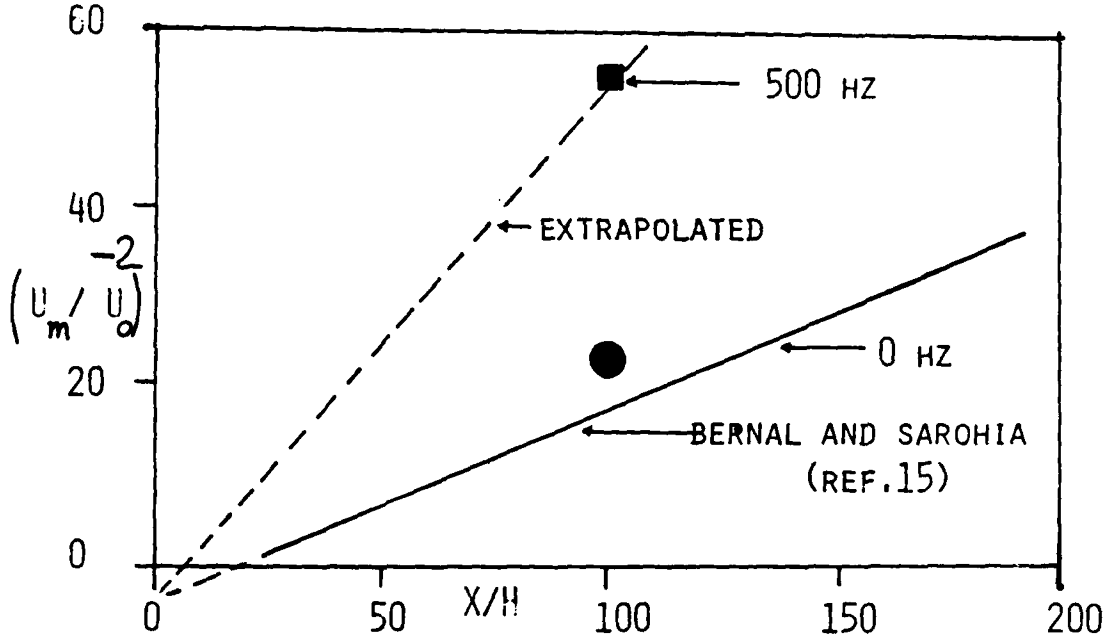


FIG.17 — COMPARISON OF STROUHAL NUMBERS



X/H= 15

H=0.254 INCH
MACH No=0.25

$ST_E=0.0611$

$ST_N= 1.325/(X/H +6.62)$
$=0.056$

X/H=100

$ST_E= 0.27$

$ST_N= 0.012$

FIG.18 COMPARISON OF EXCITED AND NATURAL STROUHAL NUMBERS IN BERNAL AND SAROHIA EXPERIMENTS

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